

# Non-adiabatic dissociation of molecules and BEC loss due to shock-waves

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Recent experiments have shown the likely appearance of coherent BEC atom-molecule oscillations in the vicinity of a Feshbach resonance. In addition, a new loss mechanism was observed, whereby the loss of atoms from the BEC is inversely dependent on the rate of change of the applied magnetic field. We present here a phenomenological model which gives a good description of the scaling properties of this new decay process, by attributing it to non-adiabatic dissociation of molecules by a propagating shock-wave. The model has only two free parameters, which specify the size of the "shocked-region", and can be readily tested by future experiments.

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In a recent series of papers the coherent creation of molecules from an atomic BEC close to the Feshbach resonance, was demonstrated [1, 2]. Both sets of experiments have the following principle characteristics. In these experiments a stable  $^{85}\text{Rb}$  BEC (at initial field  $B_i$ ) was subjected to a well controlled linear magnetic field pulse which brought it over a certain rise time  $t_r$  to a final field  $B_f$ , close to the critical field  $B_0 \simeq 154.9\text{G}$  of the Feshbach resonance. After a certain holding time  $t_h$  the field was ramped back to the initial value and the BEC was imaged. There was the distinct periodic appearance of a hot ( $\sim 150\text{nK}$ ) burst of atoms, and an unseen component, all of which remained coherent with the atomic BEC component. The unseen component is presumably the molecular component, since the Rabi frequency for the periodic change agrees with the energy difference between the free atoms and the bound molecular level  $E_{am}(B_f)$  [1, 3].

In addition to the periodic decrease and revival of the BEC, the results indicate an new mechanism of loss, which is seen to be much faster than the atomic two- and three-body inelastic loss rates [6]. All attempts to explain this loss in terms of adiabatic dynamics, treating the BEC as isotropic and uniform, have not been successful [2, 4]. It is therefore useful to try a different approach. The decrease in the atomic BEC could be due to molecules being formed or dissociated non-adiabatically, so that they do not take part anymore in the coherent oscillations [1]. One possible non-adiabatic mechanism is the creation and propagation of shock waves in the atomic-molecular cloud. Shock waves in a classical gas are supersonic discontinuities in the temperature, entropy, pressure and density [5], with all these quantities being increased by the passing shock-wave. Similar dynamic discontinuities in the trapped cloud can result in non-adiabatic dissociation of molecules and therefore loss of coherence of the resulting atoms with respect to the atomic BEC. It is this process which we shall describe using a phenomenological model here. We will not attempt a full simulation of the dynamics of the atomic and molecular clouds, but will describe the scaling of BEC loss due to such a process.

We begin by giving a qualitative description of mechanisms which can cause the appearance of shock-waves in the trapped cloud, due to the rapid change in the applied magnetic field. When the magnetic field is changed from its initial value  $B_i \sim 166\text{G}$  to its final value  $B_f$  close to the Feshbach resonance, the elastic atomic scattering length  $a$  changes by a factor of up to [2]  $\sim 4000$ , given by [1]

$$a = a_{bg} \left( 1 - \frac{\Delta}{B - B_0} \right) \quad (1)$$

with  $a_{bg} = -450a_0$ ,  $a_0 = 0.053\text{nm}$  and  $\Delta = 11\text{G}$ .

The equilibrium value of the density, using the usual Thomas-Fermi limit [7], is:  $n_{eq} \propto a^{-3/5}$ . The BEC therefore finds itself with the initial density  $n$ , which is much larger than the new equilibrium density  $n_{eq}$  that corresponds to the new scattering length  $a(B_f)$ . This means that the BEC cloud wants to greatly expand in response to the increase in  $a$ . The new equilibrium chemical potential  $\mu_{eq} = 4\pi\hbar^2 n_{eq} a / m \propto a^{2/5}$  is also very different from the chemical potential at which the cloud finds itself prior to any expansion, i.e.  $\mu = 4\pi\hbar^2 n a / m$ .

The expansion of the cloud to the new equilibrium size happens over a relatively long time scale, given by the largest trap frequency, which in the experiments is  $\tau_{trap} \simeq 30\text{ms}$ . But even before the cloud has time to readjust, the density begins to change through the propagation of density (sound) waves, similar to the case of an expanding classical gas. Rarefaction waves at the BEC surface converge on the axis of symmetry and reflect as a shock-wave (Fig.1). Referring to a detailed simulation of a similar dramatic change in the scattering length [8], we note that the imploding dynamics of the BEC create localized spikes of density (estimated to be up to  $10n$ ), of lateral size [8]  $W \sim 0.1\mu\text{m}$ . The width of the "shocked region"  $W$  is an essential parameter in our model (Fig.1).

Another source of perturbation which can cause the shock-waves to appear, is the coherent conversion of atoms into molecules. This process will not be uniform in amplitude, being denser in the middle of the cloud, or in its frequency, due to the different local magnetic

field across the cloud. The BEC will therefore have a nonuniform density of molecules, oscillating (on average) at the Rabi frequency [1, 3] 10 – 40kHz, depending on the holding field  $B_f$ . This time scale of 100 – 20 $\mu$ sec is of order of the time-scale of the observed loss rate.

Our premise is therefore the following: when the magnetic field is suddenly changed, acoustic waves propagate in the cloud in an attempt to restore the uniformity of the chemical potential, which is nonuniform due to the density profile of the cloud. Additionally, the BEC will be perturbed by an oscillating and nonuniform density of molecules. The consequent fluctuations (waves) in density will result in reverberating shock-waves. Note that by the term shock-waves, we mean in general a propagating, non-adiabatic excitation.

We estimate the amplitude of the shock-waves to be proportional to the gradients of chemical potential which form across the BEC due to the finite time it takes an acoustic wave to traverse the relevant region of the cloud. The discontinuity in the chemical potential at the shock front  $\Delta\mu$ , is therefore estimated to be the accumulated change in  $\mu$  over the time  $\tau = W/v_s$  it takes a sound wave to cross the "shocked-region" of size  $W$ , with the velocity of sound given by the standard expression [7]:  $v_s = \sqrt{\mu/m}$  (where we use the average density  $\langle n \rangle$  and the velocity of sound at the holding field  $B_f$ ). Note that weak shock-waves propagate at the speed of sound [5]. The chemical potential change, accumulated over the time  $\tau$  is

$$\Delta\mu(\tau) = \mu(\tau) - \mu_0 \simeq 4\pi\hbar^2 n a(\tau)/m \quad (2)$$

(where  $\mu_0 = 4\pi\hbar^2 n a_0/m$ ,  $a_0 = a_{bg} (1 - \Delta/(B_i - B_0)) \simeq -2\text{\AA}$ ), where

$$\begin{aligned} a(\tau) &= a_{bg} \left( 1 - \frac{\Delta}{B(\tau) - B_0} \right) \\ B(\tau) &= \begin{cases} B_f + (B_i - B_f) \frac{t_r - \tau}{t_r} & (t_r \geq \tau) \\ B_f & (t_r < \tau) \end{cases} \end{aligned} \quad (3)$$

describing the linear change in the magnetic field with time [2]. The dependence on the rise time  $t_r$  is therefore clear: the faster the rise, the larger are the chemical potential gradients created in the "acoustic" time  $\tau$ , and the resulting amplitude of the shock-waves.

Note that our treatment is inherently dependent on the inhomogeneity of the trapped cloud (Fig.1); in an infinitely uniform cloud there will be no shock waves. The process of shock-wave creation, even though we do not describe it here explicitly, depends on inhomogeneities which propagate in the cloud. We further immediately conclude that the decay time-scale  $\tau$  is largely independent on the BEC density  $n$ , as was found [2]. This behavior arises if the width of the "shocked-region"  $W$  and its length, are proportional to the equilibrium radius of the initial BEC, which is  $\propto n^{1/2}$ , while the sound velocity is also  $v_s \propto n^{1/2}$  [7].

The sound velocity is given by the magnetic field during the hold time, i.e. closest to the Feshbach resonance.

For  $B_f = 156.7\text{G}$  we have  $v_s \simeq 8\text{mm/sec}$ , for initial BEC density  $\langle n \rangle = 1.9 \times 10^{13}\text{cm}^{-3}$  [2]. To compare our calculation with the measured data [2], we used the measured decay time [2]:  $\tau = W/v_s = 13.2\mu\text{sec}$ , which corresponds to  $W \simeq 0.1\mu\text{m}$ .

We now propose that these shock waves excite the molecules non-adiabatically and create pairs of atoms, which are therefore lost from the BEC (a similar mechanism of molecular excitation/decay was mentioned in [3]). For the dissociation probability per molecule, due to the passing shock-wave, we assume a Boltzman-like factor:  $p(\tau) = \exp(-E_{am}/\Delta\mu(\tau))$ . In a classical gas a passing shock front heats the medium, and the energy jump at the front,  $\Delta\mu$ , plays the role of effective temperature [5]. Assuming that the shock-waves propagate over the width  $W$  at constant speed  $v_s$ , and cover a constant fraction  $f$  of the cloud (i.e. the "shocked-region"), the rate of loss of BEC is given by

$$\begin{aligned} \frac{dN_f}{dt} &= -\frac{N_f p(\tau)}{\tau} \\ \Rightarrow N(t_r)/N_0 &= f e^{-t_{tot} p(\tau)/\tau} + (1-f) \end{aligned} \quad (4)$$

where we took the total time for the shock-wave depletion process to be empirically  $t_{tot} = t_h + t_r/4$  [2],  $N_f$  is the number of atoms in the "shocked region", which initially is equal to  $fN_0$ . The parameter  $f$  is introduced in order to take into account the observation that the loss mechanism we describe here affects only a finite fraction  $f \simeq 90\text{--}60\%$  of the cloud (Fig.2 of [2]). A possible reason for this behavior could be that the elongated shape of the cloud makes the conditions for effective shock-wave creation and subsequent molecular dissociation appear only along its central part (Fig.1). This effect could explain why the proportion of the cloud which is affected by this loss mechanism is smaller in the case of the cloud with the smaller density [2]. This BEC will be shorter and therefore have a proportionately shorter central "shocked" region. The two free parameters of our model are therefore the width  $W$  (which determines  $\tau$ ) and the relative number of atoms  $f$  in the "shocked-region", out of the total number of atoms in the cloud.

To take into account the background processes of two- and three-body inelastic loss rates [6], we next multiply  $N(t_r)/N_0$  (4) by:  $\exp[-t_h/\tau_{2-3}]$ , with a typical decay time of  $\tau_{2-3} \simeq 0.12 \times 10^{-2}\text{sec}$  (in the vicinity of the Feshbach resonance [6]).

In Fig.2 we compare our calculated fraction of remaining BEC  $N(t_r)/N_0$  (Eq.(4)) as a function of  $t_r$ , for different hold times  $t_h$ , with the experimental data [2]. In the limit of vanishing rise time  $t_r$ , the fraction of the remaining BEC shows an exponential decay with the hold time  $t_h$  (Fig.2 of [2]). For increasing rise time we first see the increasing loss, as long as  $t_r < \tau$ , simply due to the increase in the overall time spent close to the Feshbach resonance. As soon as  $t_r > \tau$ , the loss is decreased, due to weakening shock-wave amplitude (2,3). The overall agreement is very good. The discrepancy at the longest holding time ( $t_h = 100\mu\text{sec}$ ) arises from the fact that

the reverberating shock-waves weaken with time, making longer holding times relatively less effective. This effect is not taken into account in Eq.(4), where we assumed that the dissociation probability  $p(\tau)$  is constant with time. We are therefore overestimating the loss of BEC for the longer holding times. A much better agreement is achieved for the case of  $t_h = 100\mu\text{sec}$ , if an effectively reduced value of  $t_h \sim 50\mu\text{sec}$  is used in the calculation (4), describing the decay of the shock-waves (dashed-line in Fig.2). The background decay due to two- and three-body processes [6] is shown by the dotted line.

In Fig.3 we compare our calculation (4), for a constant holding time  $t_h = 1\mu\text{sec}$  (Fig.4 of [2]), and varying final field  $B_f$ . The velocity of sound, and therefore the decay time  $\tau$ , both depend on the magnetic field  $B_f$ , with  $\tau$  decreasing as we approach the resonance field  $B_0$ . Additionally, the dependence of the dissociation energy  $E_{am}$  on the magnetic field was previously measured [1]. Again we find a good agreement, except for the longer rise times and closest approach to the resonance. At this field, our empirical assumption of  $t_r/4$  being added to the overall decay period is questionable, with a larger proportion probably active. On the other hand, this means that the shock-waves have decayed for a longer time too, resulting

in our overestimation of the BEC loss, as discussed above in relation to Fig.2.

To conclude, we have presented a phenomenological model which attributes the loss of atomic BEC to non-adiabatic dissociation of molecules by imploding shock-waves, created as a result of the rapid change in the magnetic field. This simple model appears to capture the main physical mechanism at work, as it describes the correct dependence of the observed BEC loss on the various physical parameters. Rigorous numerical simulations are needed in order to substantiate this proposal. It could be interesting to test this model further by repeating the experiments with BEC clouds of different geometries (e.g. prolate vs. oblate), and by producing shock-waves in controlled regions of the cloud by applying time-dependent and spatially non-uniform electro-magnetic fields.

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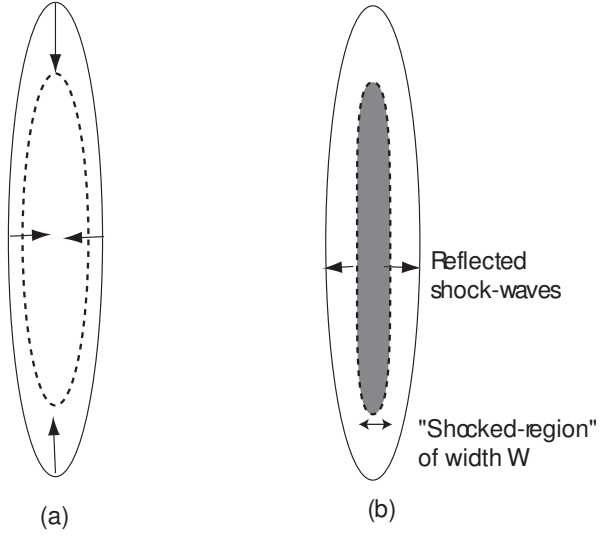


FIG. 1: A schematic illustration of our proposed scenario, whereby (a) imploding acoustic (rarefaction) waves are (b) converging on the axis of symmetry to produce a central "shocked-region" (dark region), where the non-adiabatic molecular dissociation takes place.

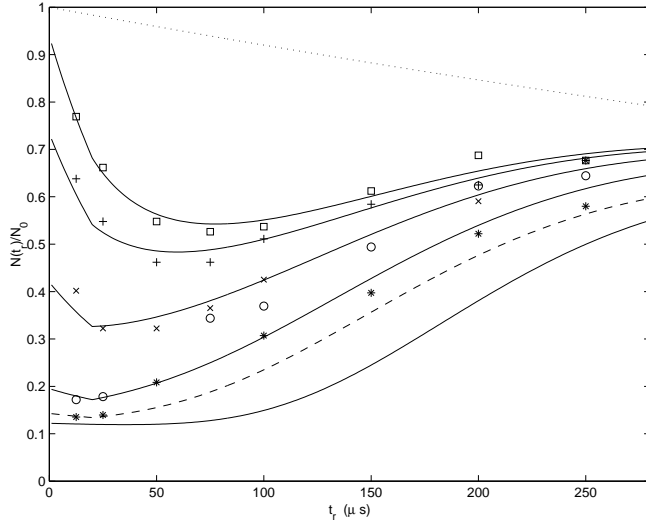


FIG. 2: The calculated (solid lines, Eq.(4)) and measured [2] (symbols) remaining fraction of atomic BEC as a function of the rise time  $t_r$ , for different holding times  $t_h = 1, 5, 15, 35, 100 \mu sec$  (from top to bottom). The dotted line gives the background decay due to two- and three-body processes [6]. The dashed line describes the calculation for a holding time of  $t_h = 50 \mu sec$ .

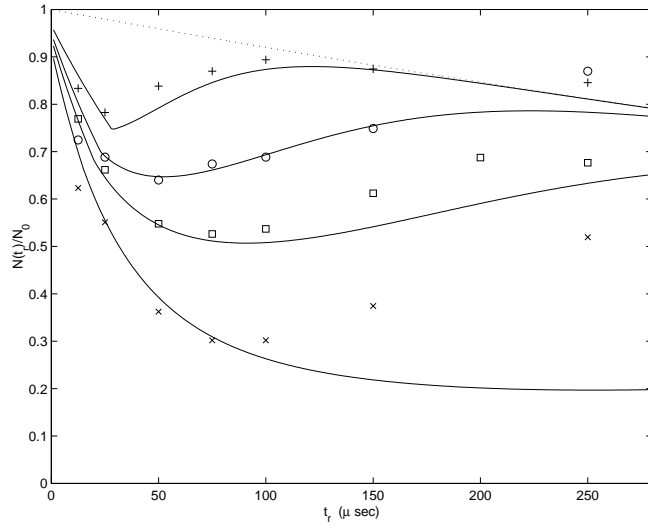


FIG. 3: The calculated (solid lines, Eq.(4)) and measured [2] (symbols) remaining fraction of atomic BEC as a function of the rise time  $t_r$ , for different holding magnetic field  $B_f = 158, 157.2, 156.7, 156$  G (from top to bottom). The dotted line gives the background decay due to two- and three-body processes [6].